Design of Embedded Systems

José Costa

Software for Embedded Systems

Departamento de Engenharia Informática (DEI)
Instituto Superior Técnico

2015-09-21

Outline

- Challenges in Embedded Systems Design
- The Embedded System Design Process
  - Requirements
  - Specification
  - Architecture
  - Component Design
  - System Integration
- Formalisms for System Design
  - Unified Modeling Language

Challenges in Embedded Systems Design

TÉCNICO LISBOA

- How much hardware do we need?
- How do we meet deadlines?
- How do we minimize power consumption?
- How do we design for upgradeability?
- Does it really work?

Difficulties in Design and Development

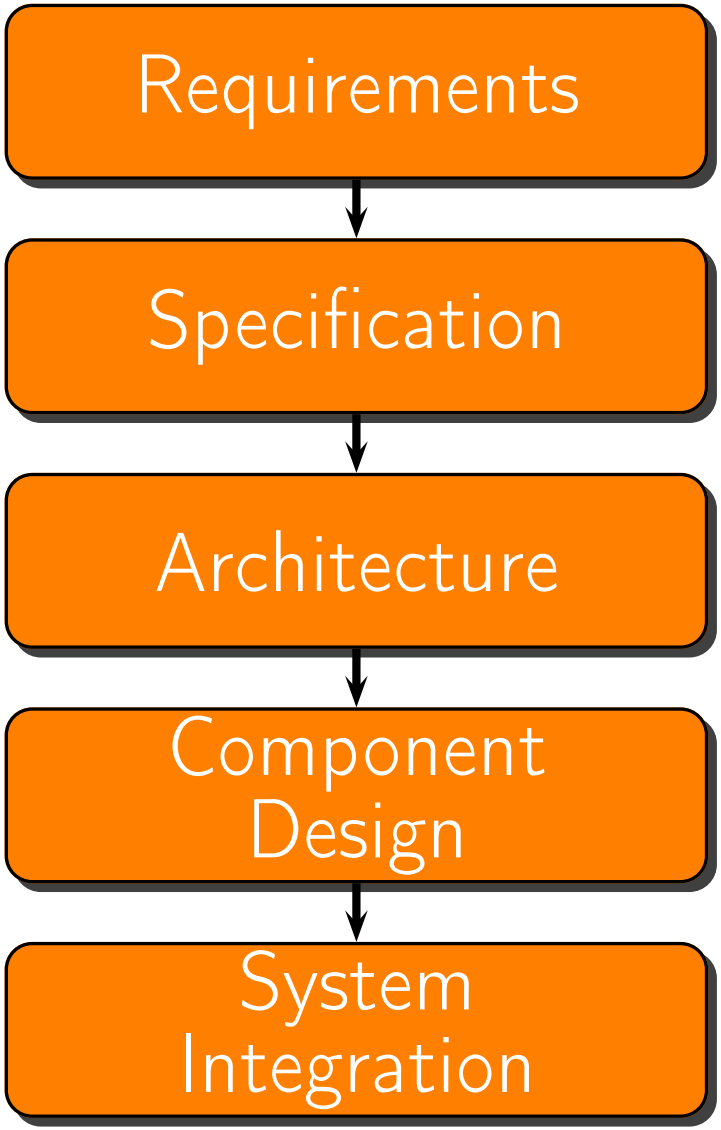
- Complex testing
  - run a real machine to have proper data
  - system must be tested in the embedded machine
- Limited observability and controllability
  - sometimes no keyboard or screen!
  - in real-time systems it's not easy to stop the system to see what is going on
- Restricted development environments
  - much more limited than in PCs
  - usually compile code in PC and download it to embedded system

Design Methodologies

A design methodology is a procedure for designing a system

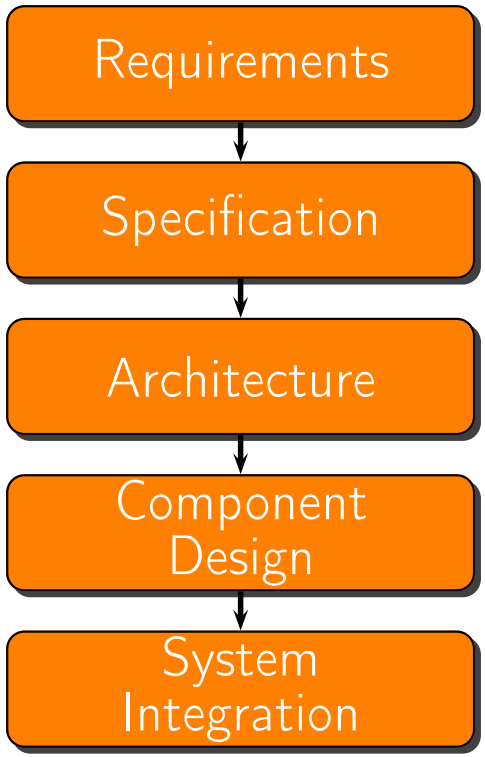
- Understanding your methodology helps you ensure you didn't skip anything
- Compilers, software engineering tools, computer-aided design (CAD) tools, etc., can be used to
  - help automate methodology steps
  - keep track of the methodology itself
- Better communication between team members
  - what they are supposed to do
  - what they should receive
  - when they have completed their assigned steps

Levels of Abstraction



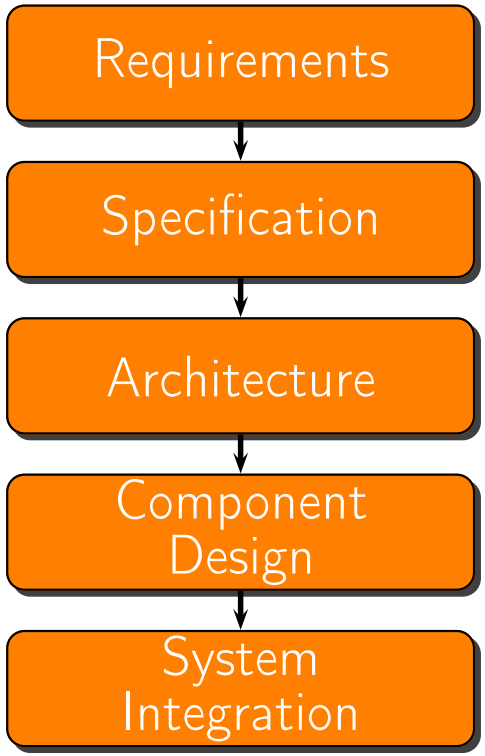
Top-down vs. Bottom-up

- Top-down design
  - start from most abstract description
  - work to most detailed
- Bottom-up design
  - work from small components to big system
- Real design uses both techniques



Design Goals

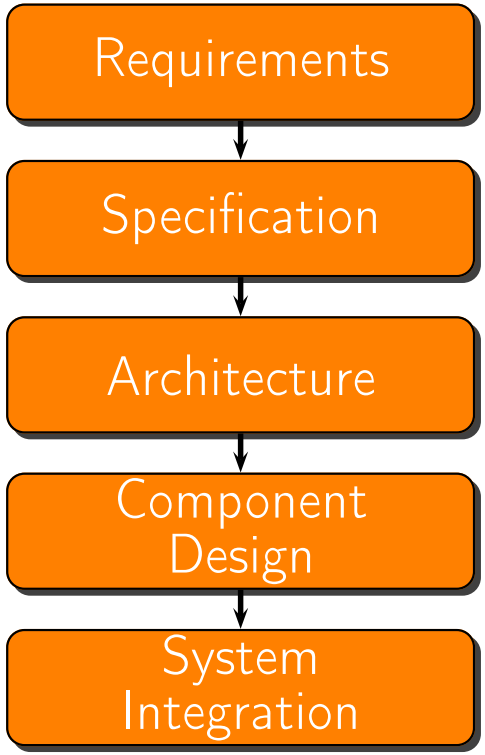
- Performance
  - Overall speed, deadlines
- Functionality and user interface
- Manufacturing cost
- Power consumption
- Other requirements (physical size, etc.)



Stepwise Refinement

At each level of abstraction, we must

- analyze the design to determine characteristics of the current state of the design
- refine the design to add detail
- verify that it meets all system goals
  - cost, speed, ...



Requirements

Plain language description of what the user wants and expects to get

- May be developed in several ways
  - talking directly to customers
  - talking to marketing representatives
  - providing prototypes to users for comment
- Requirements end up being the specification
  - containing enough information to begin designing the system architecture

Requirements vs Specification

Consumers:

- are not embedded system designers
- see mostly users' interactions
- most of the time have unrealistic expectations as to what can be done within their budgets
- have a different language

Translating from requirements to specification (from the consumer's language to the designer's)

- capturing a consistent set of requirements from the customer
- massaging those requirements into a more formal specification

Functional vs. Non-functional Requirements

- Functional requirements
  - output as a function of input
- Non-functional requirements
  - time required to compute output
  - cost
  - size, weight, etc.
  - power consumption
  - reliability
  - ...

Non-functional Requirements

- Performance
  - major consideration for the usability of the system and its ultimate cost
  - may be a combination of soft performance metrics and hard deadlines
- Cost
  - manufacturing costs (e.g. components, assembly)
  - nonrecurring engineering (NRE) costs (e.g. personnel, designing the system)
- Physical size and weight
  - depends on the application
- Power consumption
  - important not only in battery-powered systems
  - specified in terms of battery life

Validating The Requirements

- Requires understanding what people want and how they communicate it
- User interface requirements can be refined by using a mock-up
  - may be executed on a PC
- Physical, nonfunctional models of devices can also help
  - better idea of size and weight

Sample Requirements Form (1/3)

- name
- purpose
- inputs and outputs
- functions
- performance
- manufacturing costs
- power
- physical size/weight

Sample Requirements Form (2/3)

- name
- purpose
  - one- or two-line description
- inputs and outputs
  - types of data: analog? digital? mechanical?...
  - data characteristics: periodic? occasional? how many bits?...
  - types of I/O devices: buttons? A/D converters? video displays?...
- functions
  - more detailed description of the system
  - when the system receives an input, what does it do?
  - how do interface inputs affect these functions?
  - how do different functions interact?

Sample Requirements Form (3/3)

- performance
  - must be identified earlier to ensure that the system works properly
- manufacturing costs
  - cost has substantial influence on architecture
  - work with some idea of the cost range
- power
  - battery powered? plugged into a wall?
- physical size/weight
  - more or less flexibility in the components to use

Beyond The Requirements Form

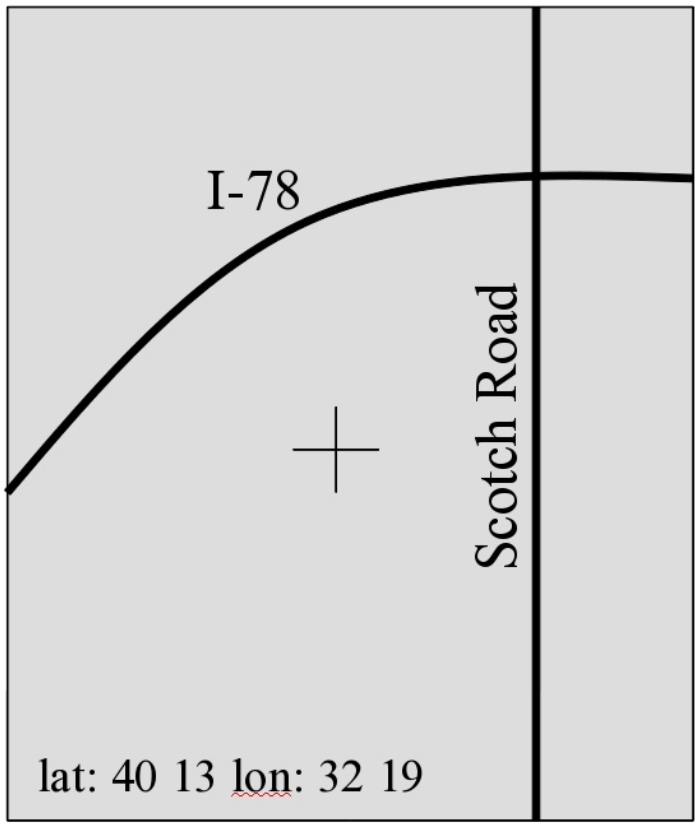
- The requirements form should be the introductory of a longer document
- After writing the requirements you should check for internal inconsistency
  - forget to assign functions to an input/output?
  - considered all modes of operation?
  - unrealistic number of features into a battery-powered, low-cost machine?

Requirements form

- name
- purpose
- inputs and outputs
- functions
- performance
- manufacturing costs
- power
- physical size/weight

Example: GPS Moving Map Requirements

- Moving map obtains position from GPS
- Paints map from local database



GPS Moving Map Needs (1/2)

- Functionality
  - for automotive use
  - show major roads and landmarks
- User interface
  - at least 400 x 600 pixel screen
  - three buttons max
  - pop-up menu
- Performance
  - map should scroll smoothly
  - no more than 1 sec power-up
  - lock onto GPS within 15 seconds

GPS Moving Map Needs (2/2)

- Cost
  - € 100 street price = approx. € 30 cost of goods sold
- Physical size/weight
  - should fit in dashboard
- Power consumption
  - current draw comparable to CD player

GPS Moving Map Requirements Form

- name: GPS moving map
- purpose: consumer-grade moving map for driving
- inputs: power button, two control buttons
- outputs: back-lit LCD 400x600
- functions: 5-receiver GPS; displays current lat/lon
- performance: updates screen within 0.25 sec of movement
- manufacturing costs: $\approx$ 30€ cost-of-goods-sold
- power: 100mW
- physical size/weight: no more than 5cm x 15cm, 350g

Specification

Serves as the contract between the customer and the architects.

- A more precise description of the system
  - should not imply a particular architecture
  - provides input to the architecture design process
- May include functional and non-functional elements
- May be executable or may be in mathematical form for proofs

Specification

- Should be understandable enough
  - so that someone can verify that it meets system requirements and overall expectations of the customer
- Should be unambiguous

Problems of unclear specifications

- implementation of wrong functionality
- system architecture may be inadequate to meet the needs of the implementation

GPS Specification

Should include

- what is received from GPS
- map data
- user interface
- operations required to satisfy user requests
- background operations needed to keep the system running
  - e.g. operating the GPS receiver

Specification vs Architecture Design

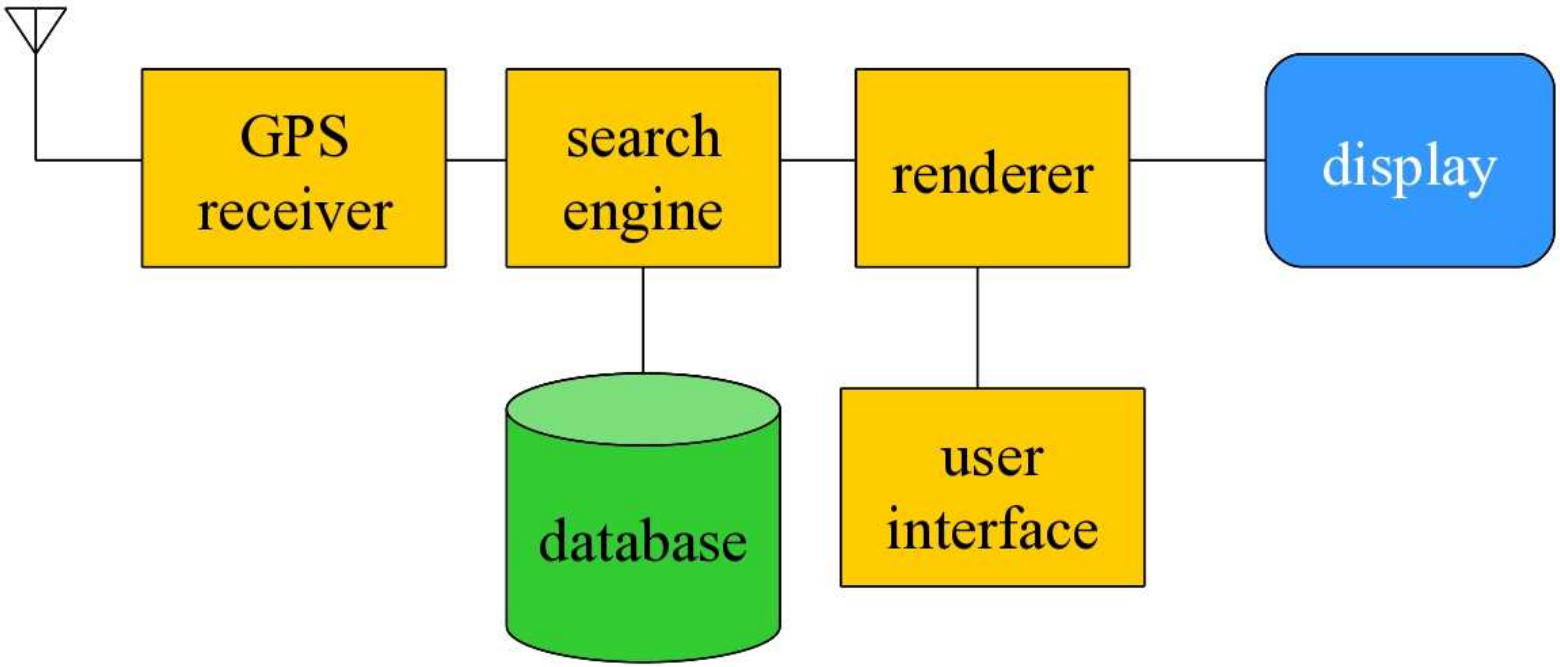
- The specification does not say how the system does things, only what the system does
- The purpose of the architecture is to describe how the system implements the functions
- The architecture is a plan for the overall structure of the system
  - it will be used later to design the components

The creation of the architecture is the 1st phase of the so called "design"

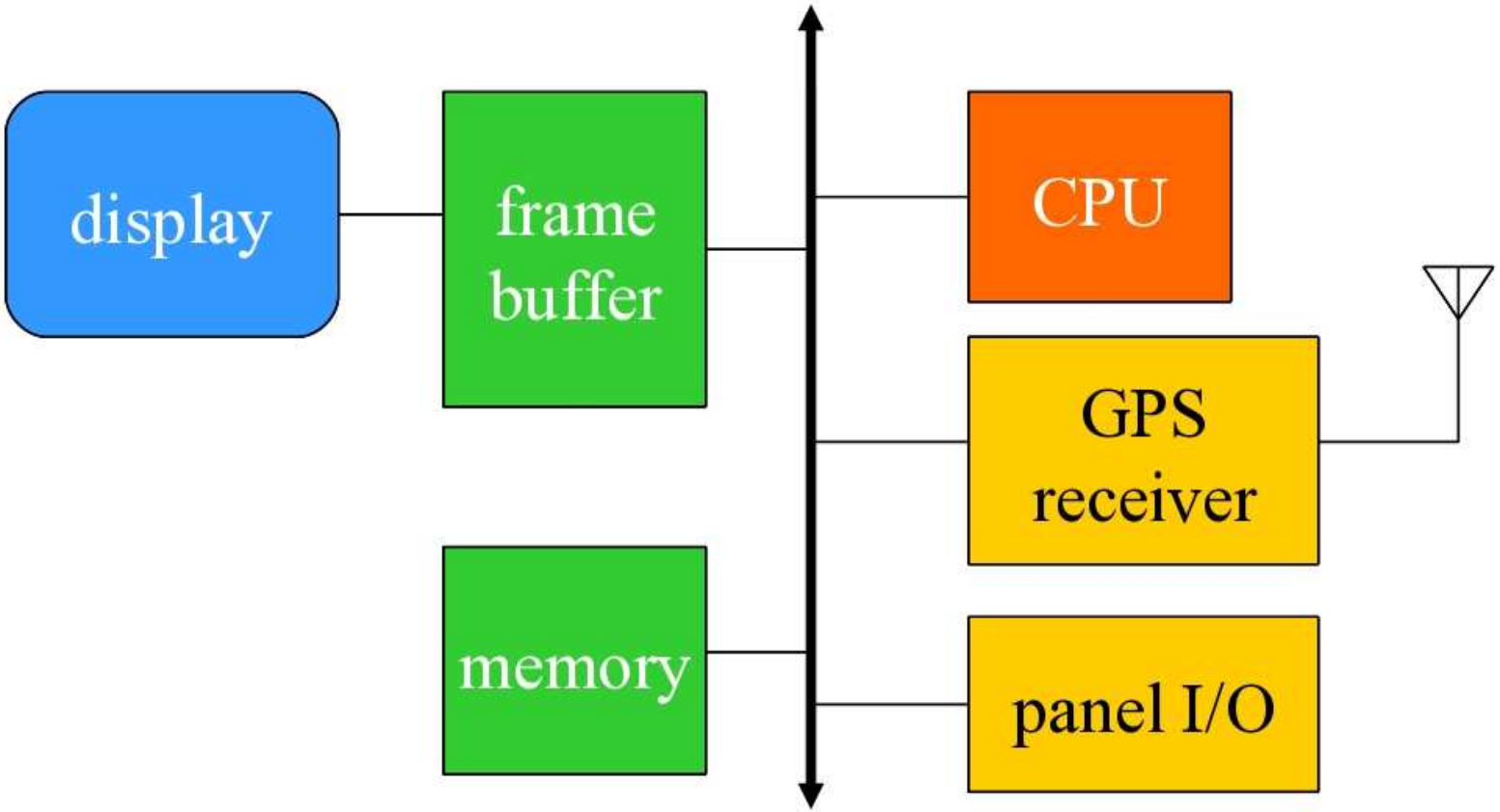
Architecture Design

- What major components go satisfying the specification?
- Hardware components
  - CPUs, peripherals, etc.
- Software components:
  - major programs and their operations
- Must take into account functional and non-functional specifications

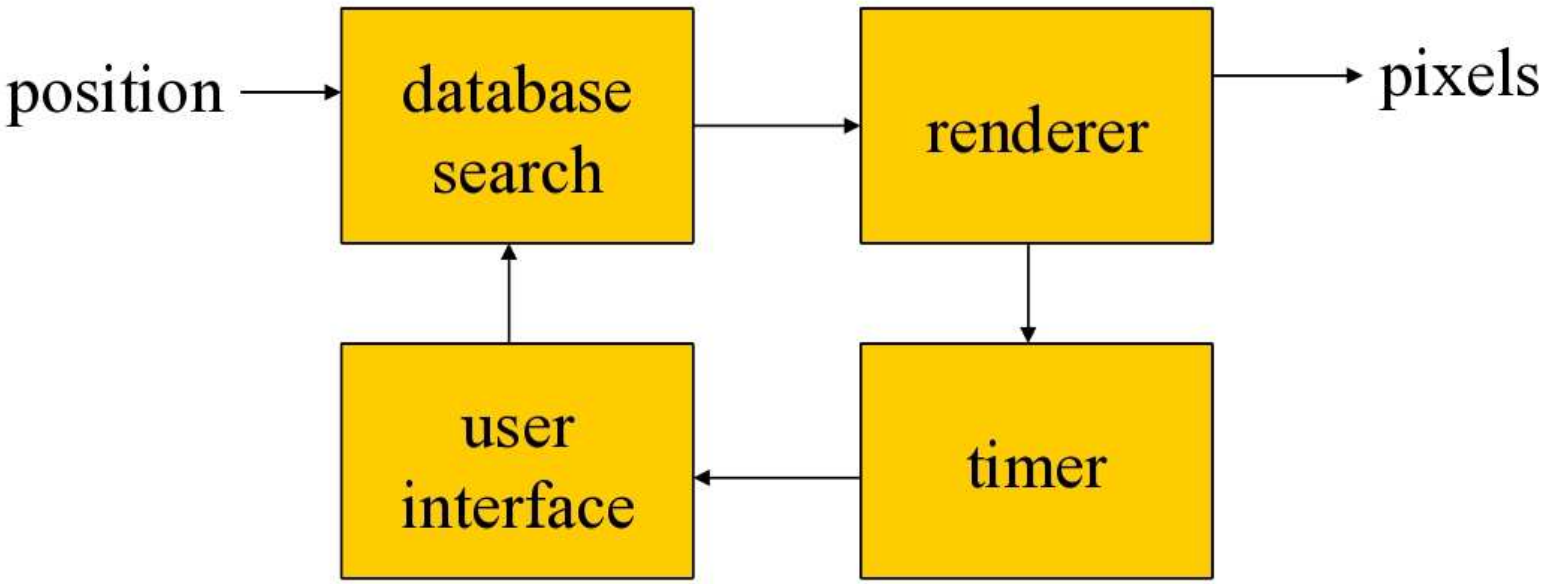
GPS Moving Map Block Diagram



GPS Moving Map Hardware Architecture



GPS Moving Map Software Architecture



Designing Hardware and Software Components

- Must spend time architecting the system before you start coding
- Some components are ready-made
  - CPU, memory chips, ...
  - some are software components
- Some can be modified from existing designs
- Others must be designed from scratch
  - at least you may have to design the board
  - custom programming

Identifying Existing Hardware And Software Components

- Much of the design process is composition of existing modules
  - Hardware boards and peripheral interfaces
  - Software modules
    - Operating System or run-time environment
    - Middleware (ex. Communications layers, RFID coding)
    - Applications

- Usually designers try to keep their usual development environment
  - Processors and low-level tools
  - Operating systems or run-time environments

System Integration

- Put together the components (hardware blocks and software modules)
- Not as easy as it sounds...
  - Many bugs appear only at this stage
  - Debugging facilities are limited
- Have a plan for integrating components to uncover bugs quickly, test as much functionality as early as possible
  - build up the system in phases
  - debug only a few modules at a time

Formalisms For System Modeling

- Need languages to describe systems
  - useful across several levels of abstraction
  - understandable within and between organizations

- Block diagrams are a start, but don't cover everything

Object-Oriented Design

- Object-oriented (OO) design: A generalization of object-oriented programming
  - encourages design to be described as a number of interacting objects
  - some objects will correspond to real pieces of software

- Object = state + methods
  - State provides each object with its own identity
  - Methods provide an abstract interface to the object

Object Oriented Concepts

- Objects represent an entity and the basic building block
- Class is the blueprint of an object
- Abstraction represents the behavior of a real world entity
- Encapsulation is the mechanism of binding the data together and hiding them from outside world
- Inheritance is the mechanism of making new classes from existing one
- Polymorphism defines the mechanism of one class existing in different forms

UML - Unified Modeling Language

- UML is a standard language for specifying, visualizing, constructing, and documenting the artifacts of software systems

- UML was created by Object Management Group (OMG) and UML 1.0 specification draft was proposed to the OMG in January 1997

A picture is worth a thousand words.

Conceptual Model of UML

- Building Blocks
  - Things
  - Relationships
  - Diagrams
- Rules
- Common Mechanisms
  - Specifications
  - Adornments
  - Common Divisions
  - Extensibility Mechanisms

UML Building Blocks

Things

- Structural
- Behavioral
- Grouping
- Annotational

Relationships

- Dependency
- Association
- Generalisation
- Realization

Diagrams

- Class Diagram
- Object Diagram
- Use Case Diagram
- Sequence Diagram
- Collaboration Diagram
- Statechart Diagram
- Activity Diagram
- Component Diagram
- Deployment Diagram

Structural Things

Structural things are the static parts of the system.

- Class - an abstraction of a set of things in the problem domain that have similar properties and/or functionality
- Interface - a collection of operations that specify the services rendered by a class or component
- Collaboration - a collection of UML building blocks (classes, interfaces, relationships) that work together to provide some functionality within the system
- Use Case - an abstraction of a set of functions that the system performs; a use case is "realized" by a collaboration

Structural Things

- Active Class - a class whose instance is an active object; an active object is an object that owns a process or thread (units of execution)
- Component - a physical part (typically manifests itself as a piece of software) of the system
- Node - a physical element that exists at run-time and represents a computational resource (typically, hardware resources)

Behavioral Things

Behavioral things are usually the dynamic parts of the system.

- Interaction - some behaviour constituted by messages exchanged among objects;
- State machine - a behaviour that specifies the sequence of "states" an object goes through, during its lifetime

Grouping Things

Grouping things provides a higher level of abstraction.

- Package - a general-purpose element that comprises UML elements - structural, behavioral or even grouping things

Annotational Things

Annotational things add information/meaning to the model elements.

- Note - a graphical notation for attaching constraints and/or comments to elements of the model

Relationships

Relationships articulates the meaning of the links between things.

- Dependency - a semantic relationship where a change in one thing causes a change in the semantics of the other thing
- Association - a structural relationship that describes the connection between two things
- Generalisation - a relationship between a general thing and a more specific kind of that thing, such that the latter can substitute the former
- Realization - a semantic relationship between two things wherein one specifies the behaviour to be carried out, and the other carries out the behaviour.

Diagrams

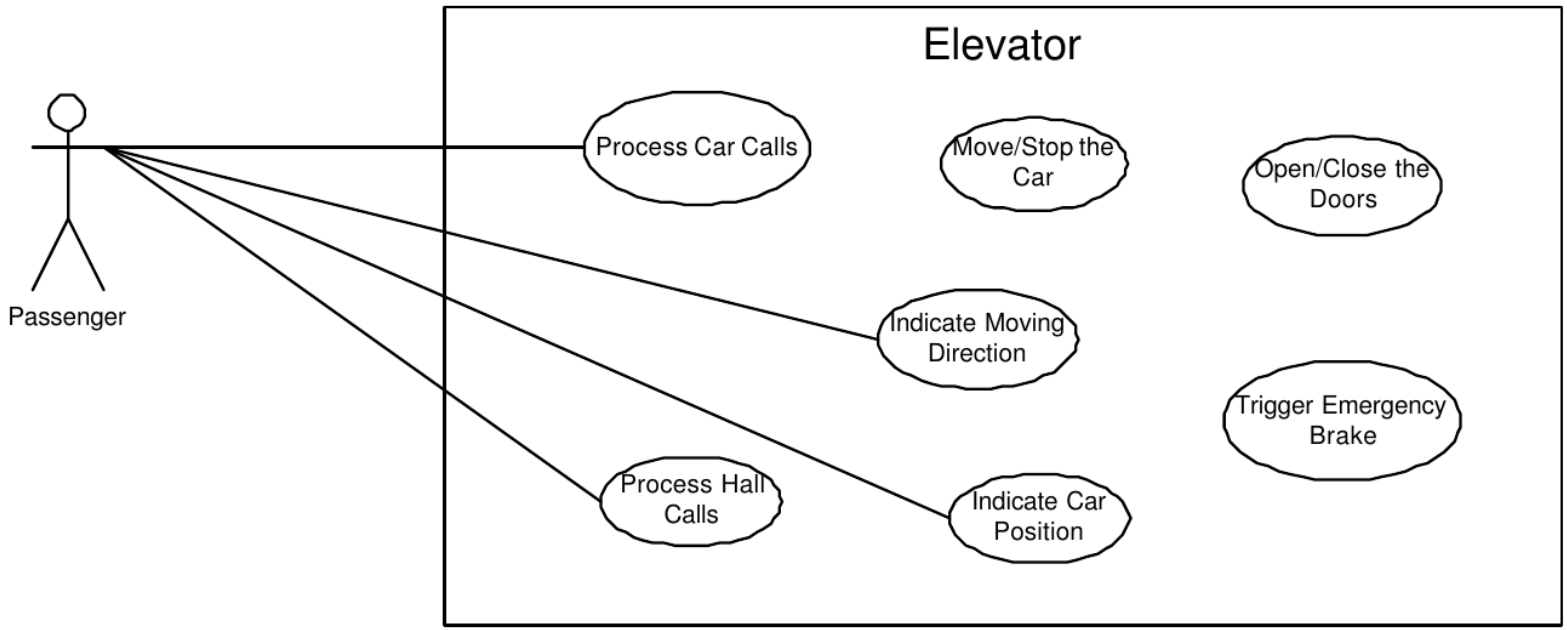
Diagrams are the graphical presentation of the model.

- Class Diagram - models the static view of the system
- Object Diagram - models the instances of things contained in a class diagram
- Use Case Diagram - models what the system is expected to do
- Sequence Diagram - models the flow of control by time-ordering

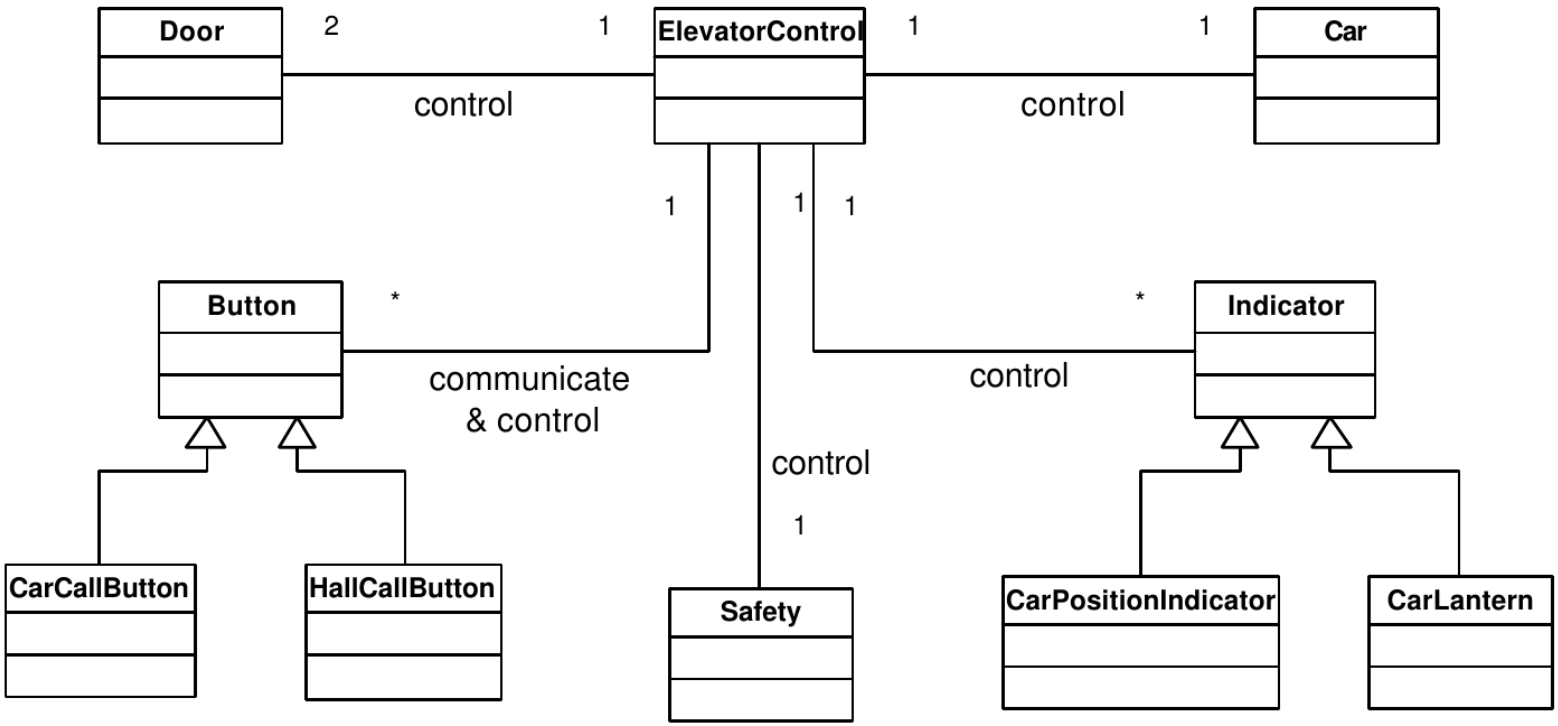
Diagrams

- Collaboration Diagram - models the interaction between objects, without the temporal dimension
- Statechart Diagram - shows the different state machines and the events that leads to each of these state machines
- Activity Diagram - shows the flow from activity to activity
- Component Diagram - shows the physical packaging of software in terms of components and the dependencies between them
- Deployment Diagram - shows the configuration of the processing nodes at run-time and the components that live on them

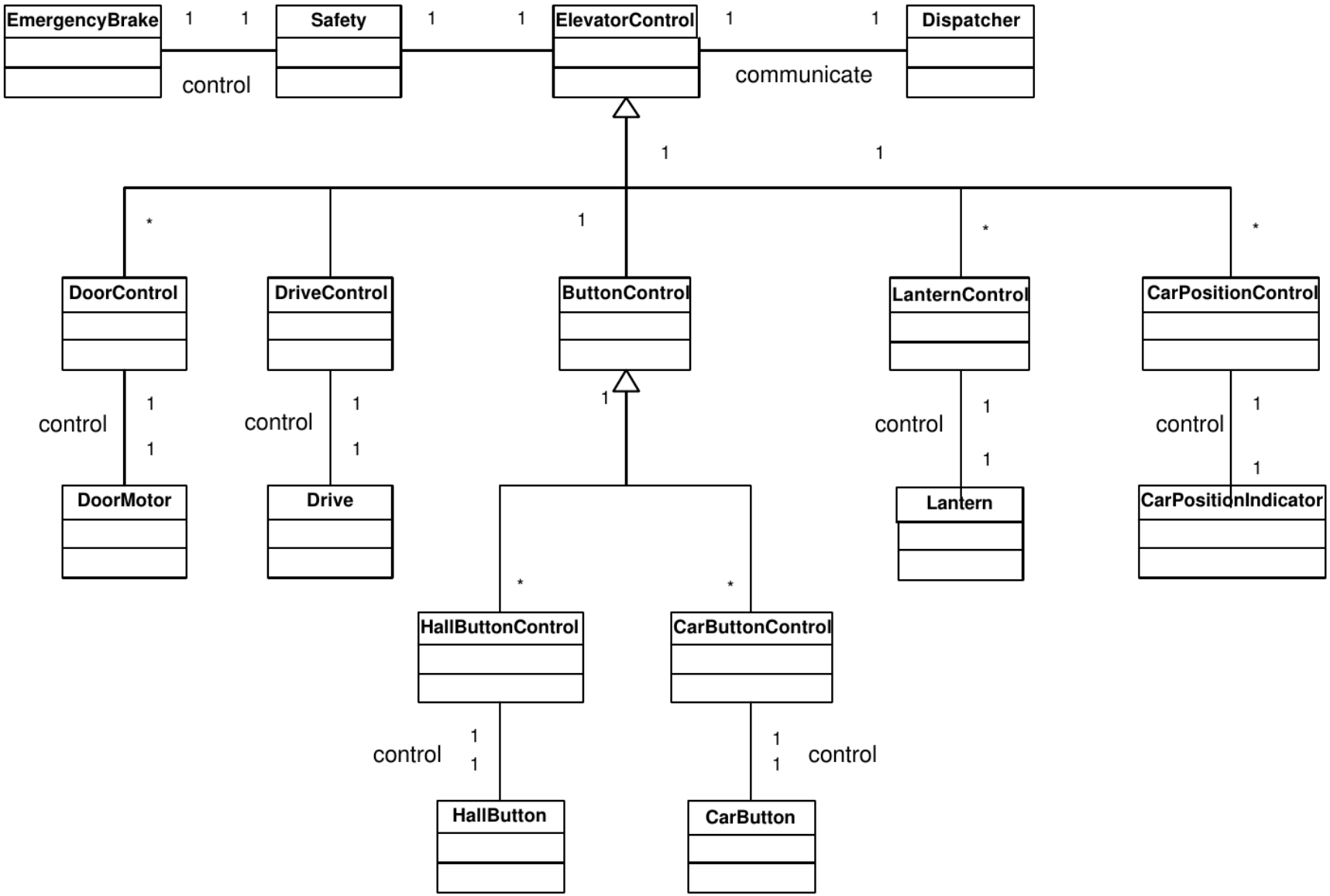
Elevator - Use Case



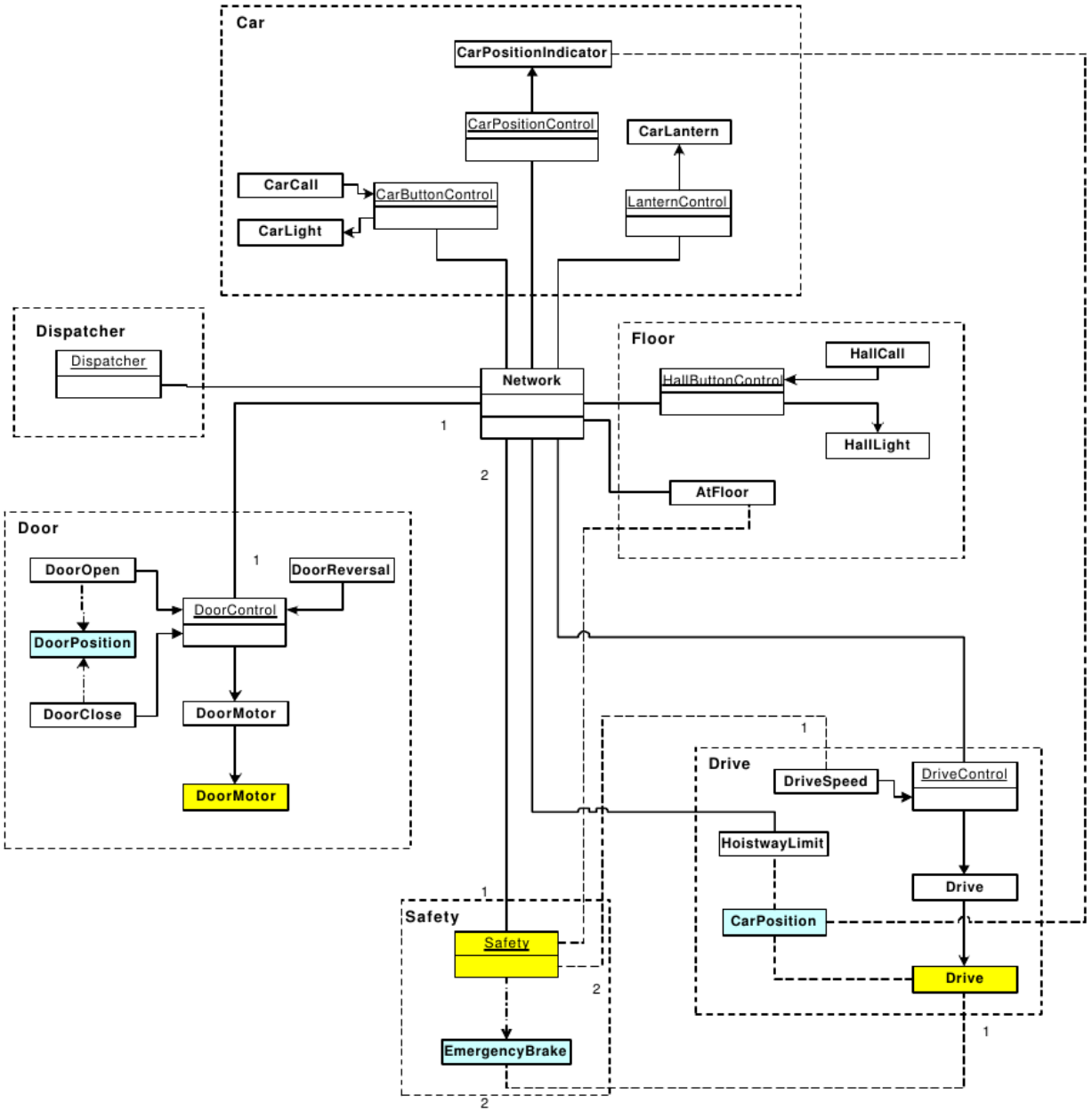
Class Diagram - Object Construction



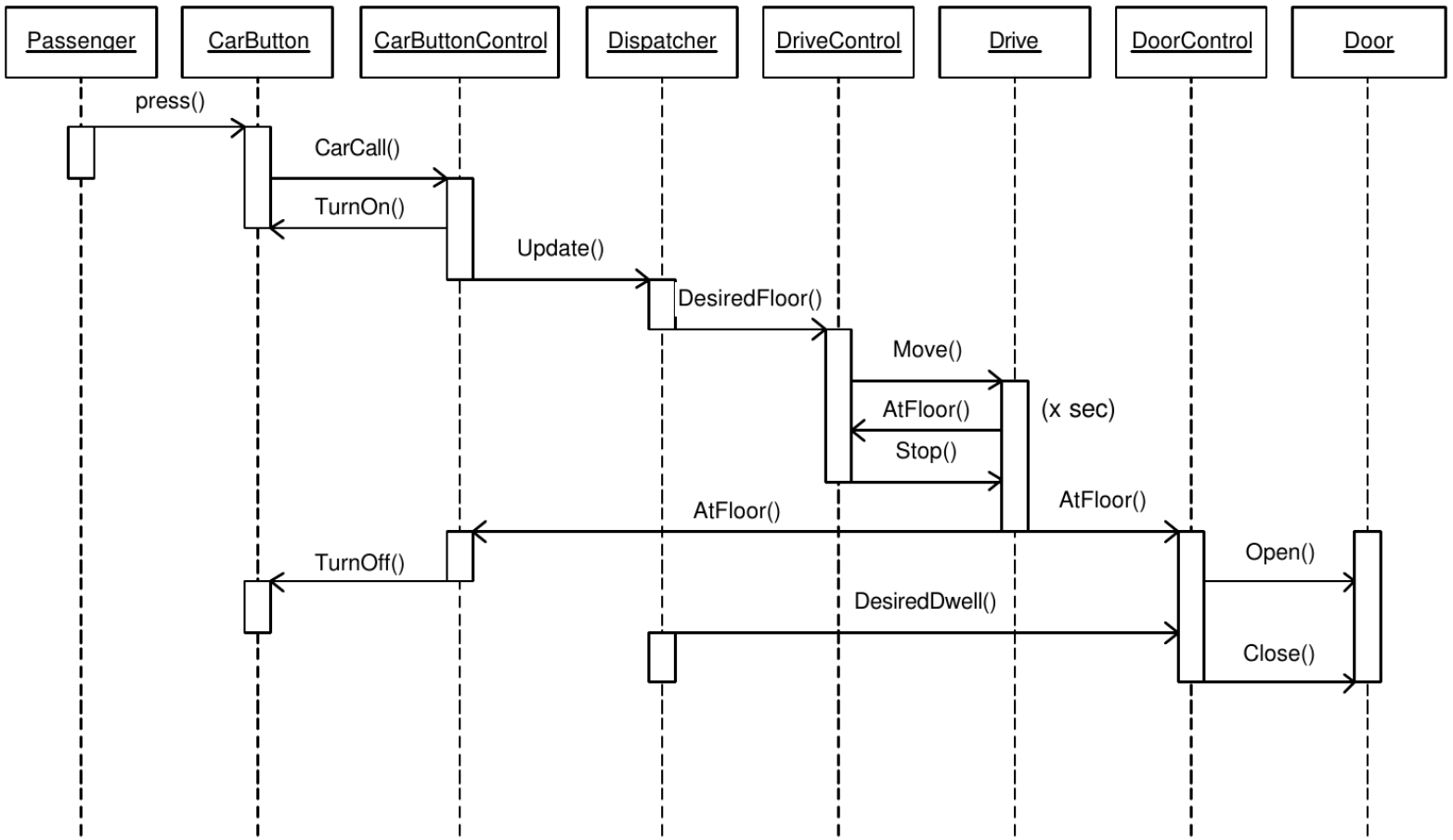
Class Diagram - Software



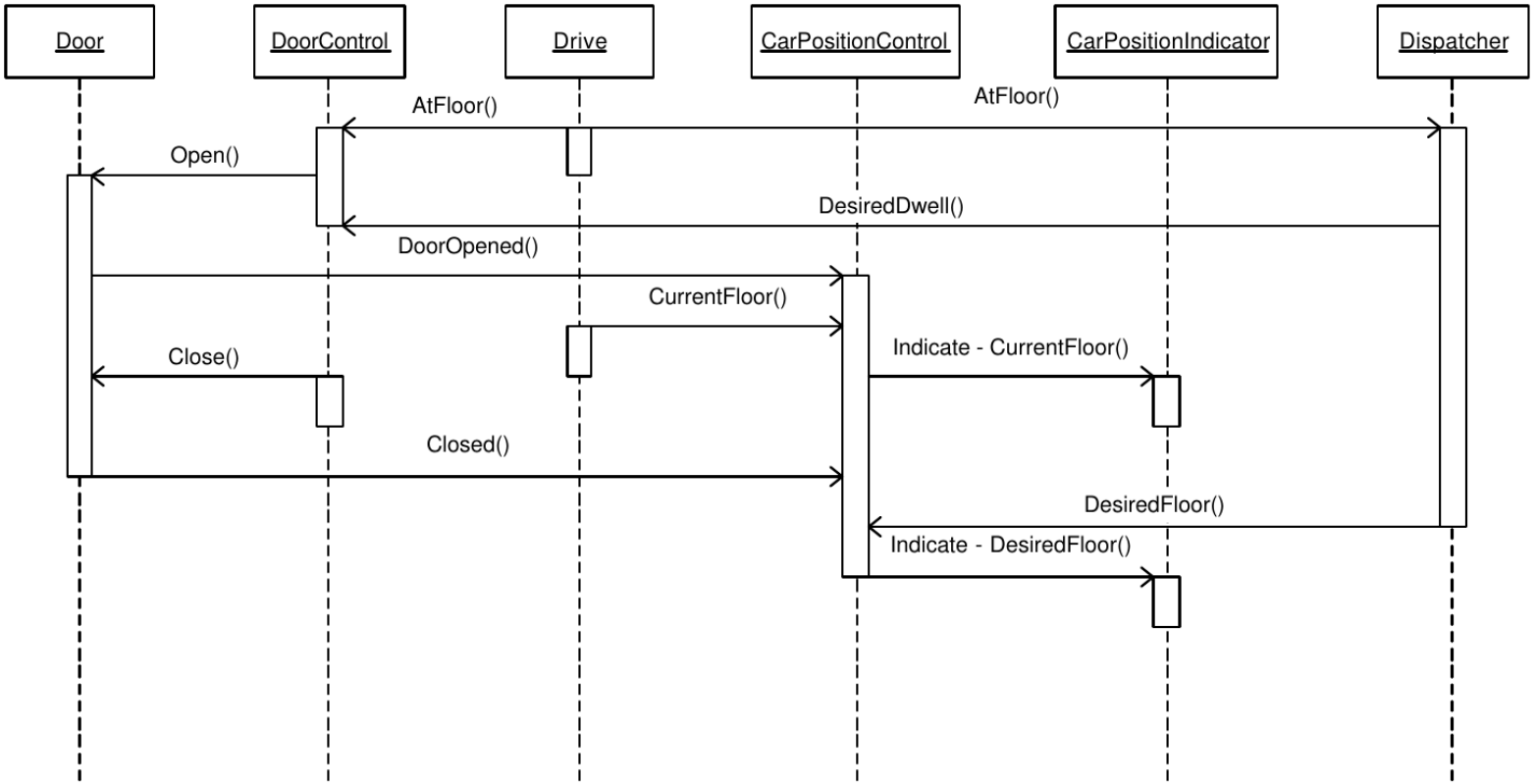
Class Diagram - System



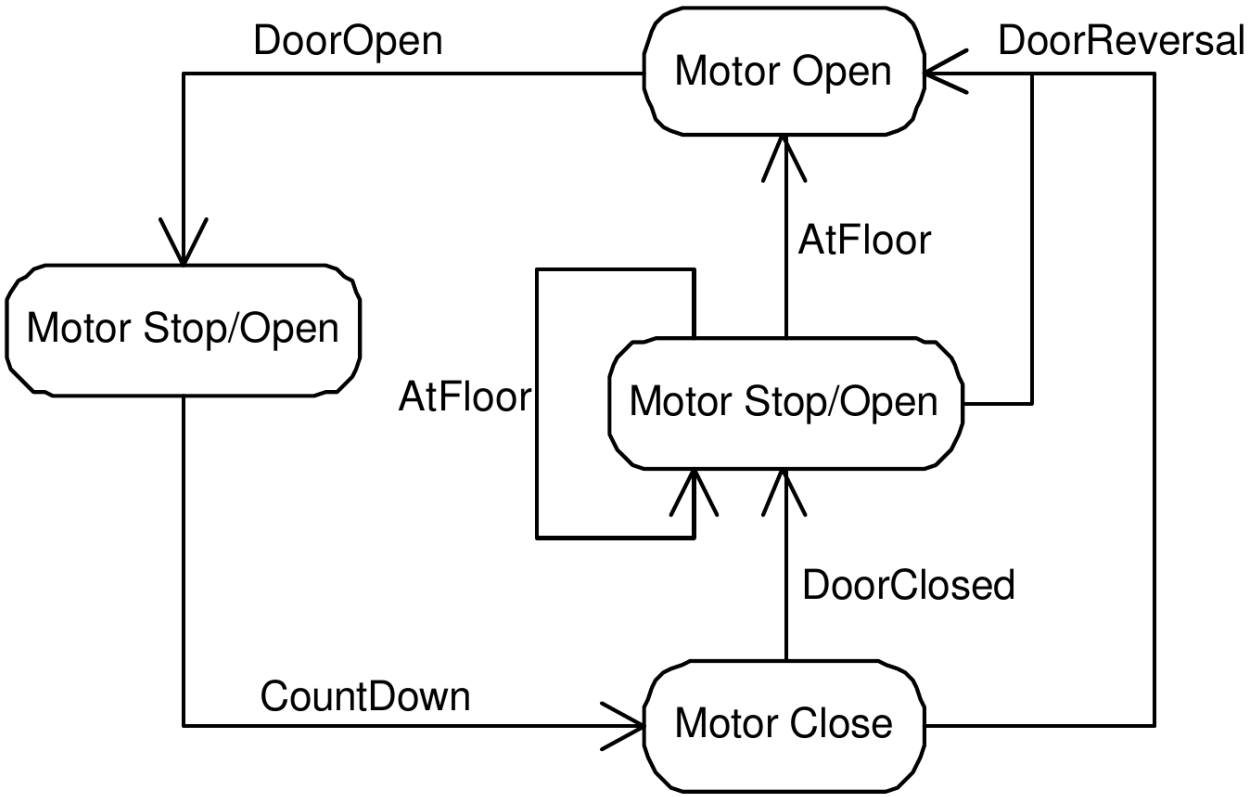
Use Case - Call Car



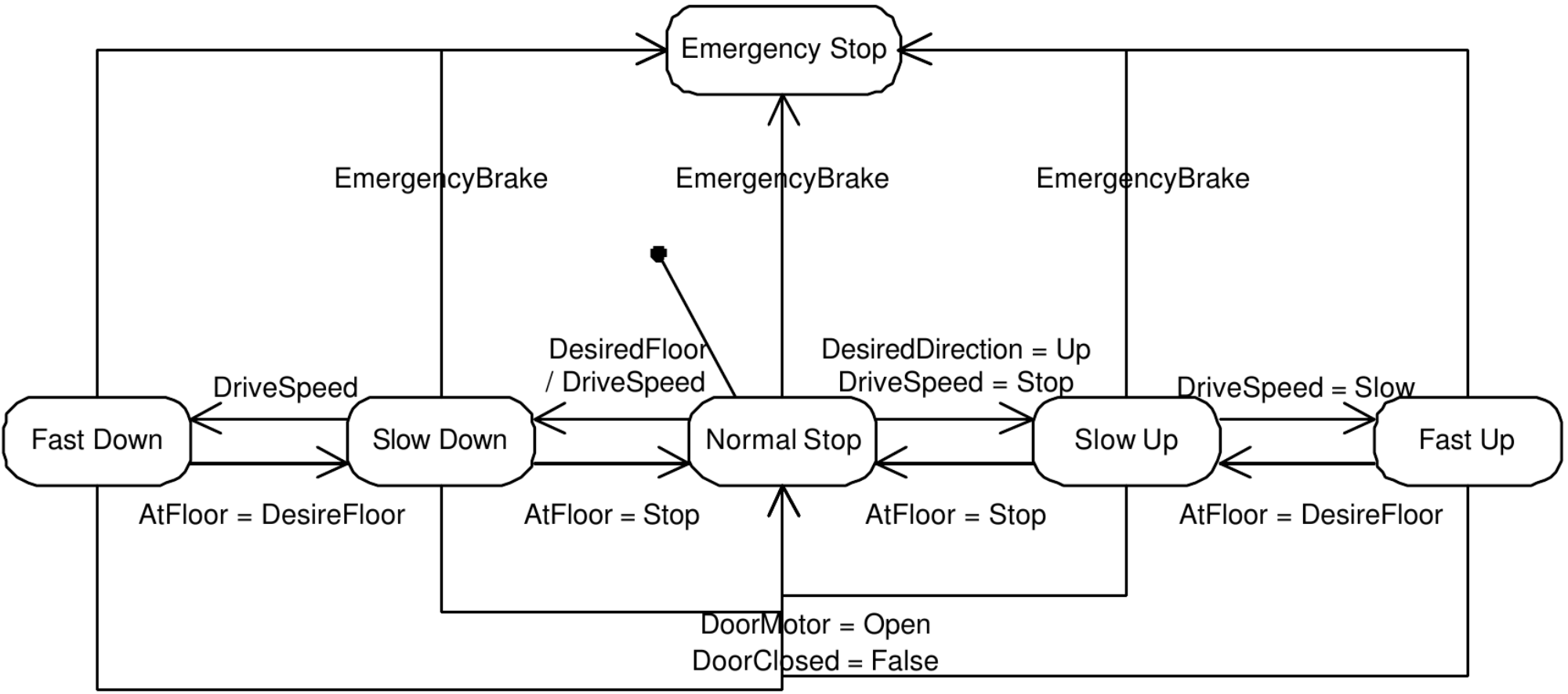
Use Case - Car Position



State Chart - Door Control



State Chart - Drive Control



- Modeling should capture the system in its entirety
- Modeling facilitates quick and efficient analysis and design and helps communicate the overall system architecture unambiguously

Principles of modeling

- model must be chosen well
- model should encapsulate different granularities
- models can make simplifying assumptions, but not hide important facts
- no single model can capture all dimensions of the complexity

Outline

- Challenges in Embedded Systems Design
- The Embedded System Design Process
  - Requirements
  - Specification
  - Architecture
  - Component Design
  - System Integration
- Formalisms for System Design
  - Unified Modeling Language

References

- Computers as Components: Principles of Embedded Computing System Design , Marilyn Wolf. Morgan Kaufman. Ch. 1.3

Next Class

- Architecture of Embedded Systems